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Conference Paper

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Beiträge zur Jahrestagung des Vereins für Socialpolitik 2013: Wettbewerbspolitik und Regulierung in einer globalen Wirtschaftsordnung - Session: Growth and Environment, No. C04-V2

Provided in Cooperation with:

Verein für Socialpolitik / German Economic Association

Suggested Citation: Springmann, Marco; Böhringer, Christoph; Rutherford, Thomas F. (2013) : Clean-development investments: an incentive-compatible CGE modeling framework, Beiträge zur Jahrestagung des Vereins für Socialpolitik 2013: Wettbewerbspolitik und Regulierung in einer globalen Wirtschaftsordnung - Session: Growth and Environment, No. C04-V2, ZBW - Deutsche Zentralbibliothek für Wirtschaftswissenschaften, Leibniz-Informationszentrum Wirtschaft, Kiel und Hamburg

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Clean-development investments: an incentive-compatible CGE modeling framework

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Abstract: The Clean Development Mechanism (CDM) established under the Kyoto Protocol allows industrialized Annex I countries to offset part of their domestic emissions by investing in emissions-reduction projects in developing non-Annex I countries. We present a novel CDM modeling framework which can be used in computable-general-equilibrium (CGE) models to quantify the sector-specific and macroeconomic impacts of CDM investments. Compared to conventional approaches that mimic CDM as sectoral emission trading, our framework adopts a micro consistent representation of the CDM incentive structure and its investment characteristics. In our empirical application based on GTAP data we show that incentive compatibility implies that CDM-implementing sectors do not suffer and overall welfare gains tend to be lower than suggested by conventional modeling approaches.

Keywords: Clean Development Mechanism, Computable General Equilibrium Modeling

1. Introduction

The Clean Development Mechanism (CDM) established under the Kyoto Protocol allows industrialized Annex I countries to offset part of their domestic emissions by investing in emissions-reduction projects in developing non-Annex I countries.¹ At the 18th Conference of the Parties (COP 18) of the United Nations Framework Convention on Climate Change (UNFCCC) in Doha, governments have agreed on a second commitment period of the Kyoto Protocol which is intended to bridge the years from 2013 to 2020 until a global agreement on climate change might become effective. As a key flexibility mechanism under the Kyoto Protocol, the CDM will continue through the second commitment period and will therefore remain in place at least until the end of this decade.

¹ The CDM has two main purposes (Article 12.2 Kyoto Protocol). For Annex I countries its purpose is to increase the cost-efficiency of fulfilling their emissions reduction commitments made under the Kyoto Protocol by utilizing low-cost abatement options in non-Annex I countries. For non-Annex-I countries its purpose is to spur sustainable development by financing projects that reduce emissions and support development.

In 2011, the UNFCCC has launched a high-level policy dialogue on the CDM to reflect on the experiences gained and how to position the mechanism going forward. Analysts note that since its inception the CDM has triggered significant investment in emissions reductions in developing countries (Gillenwater and Seres, 2011; World Bank, 2011). However, the mechanism has also been subject to considerable criticism, e.g., on issues regarding the additionality of emissions reductions or the definition of the baseline against which those reductions are to be measured (see, e.g., Paulsson, 2009).

In this paper we abstract from the political and administrative discussions surrounding the CDM and instead focus on its quantitative economic impact assessment in numerical modeling studies.² From an economic perspective, the CDM addresses a fundamental efficiency pitfall inherent in the subglobal nature of current international climate policy agreements. Under the UNFCCC framework, only industrialized countries with relatively high marginal abatement costs have agreed to binding emissions reductions, while developing countries with relatively low marginal abatement costs have not adopted such targets.³ This leaves a large potential for cost-effective emissions reduction in developing countries unexploited. The CDM⁴ attempts to increase the global cost-efficiency of subglobal abatement commitments by allowing part of industrialized countries' commitments to be met by undertaking emissions-reduction projects in developing countries.

Compared to conventional approaches, our CDM modeling framework features a micro consistent representation of the CDM incentive structure and its investment characteristics at the sector level which allows for a coherent evaluation of sectoral and economy-wide effects emerging from CDM investment decisions. Our proposed framework contributes to the existing literature in three ways. First, it allows for a more accurate economic impact assessment of the CDM. Second, it provides a clear distinction of the CDM mechanism compared to alternative regulatory climate policies that involve developing countries, such as integrated emissions trading. Third, our framework can be easily generalized to analyze other policy-relevant topics concerning clean-development investment, such as climate finance and green-growth strategies.

The remainder of this paper is organized as follows. Section 2 reviews previous CDM modeling approaches and discusses their shortcomings. Section 3 presents a stylized general-equilibrium model to document the implementation of our CDM modeling approach and highlight its differences to previous modeling approaches. Section 4 provides a stylized large-scale CGE application of the CDM implemented between the industrialized and the developing world. Section 5 concludes.

2. CDM modeling frameworks

² A substantial body of literature has formed around the CDM analyzing and proposing ways to hold the CDM in line with its dual purpose of enabling cost-efficient (and regionally independent) emissions reduction for Annex I countries and of spurring sustainable development through CDM investment in non-Annex I countries (see, e.g., Ellis et al., 2007; Boyd et al., 2009; Lecocq and Ambrosi, 2007).

³ The latest Conferences of the Parties in Copenhagen (COP-15), Cancún (COP-16), and Durban (COP-17) have brought about a voluntary pledge-and-review system. Although some developing countries, such as India and China, have contributed voluntary pledges, they have not adopted binding emissions-reduction commitments.

⁴ The CDM, if narrowly interpreted, adheres to projects. Broader approaches are categorized under the definitions of Programmes of Activities (PoAs) and sectoral CDMs (so-called sCDMs).

Modeling approaches for the quantitative impact assessment of the CDM are commonly based on computable partial equilibrium (CPE) or and computable general equilibrium (CGE) models. Partial equilibrium analyses of the CDM primarily focus on the CDM supply and assess the abatement costs and the availability of abatement options in developing countries. For that purpose, analyses such as Jotzo and Michaelowa (2002) employ marginal abatement cost (MAC) curves which can be constructed from a variety of sources, such as project-level information (Wetzelaer et al., 2007), energy system models (Capros et al., 1998; Criqui et al., 1999), and general equilibrium models (Böhringer and Rutherford 2002, Paltsev et al., 2005; Morris et al., 2012). Several studies, including Michaelowa and Jotzo (2005), Kallbekken (2007), or Böhringer and Löschel (2008), extend the simple MAC curve model to reflect transaction costs and investment risks associated with the project-based character of the CDM (see also Springmann, 2013). CPE models can, depending on the data source, capture the discrete project nature of the CDM; however, they cannot represent the economy-wide impacts resulting from market interaction and income effects.

The second modeling approach is to use computable general equilibrium (CGE) models and to represent the CDM as a form of emissions trading between industrialized countries and developing ones (see, e.g., Manne and Richels, 1999; Bernstein et al., 1999; MacCracken, 1999; Klepper and Peterson, 2005; Burniaux et al., 2009). The main virtue of the CGE approach is its comprehensive representation of market interactions through price- and income-responsive supply and demand reactions. Beyond price-induced structural change in production and consumption, CGE models can quantify efficiency implications and distributional impacts of policy measures. Yet, the common representation of the CDM in CGE models so far suffers from simplifying and potentially inconsistent assumptions. The CDM is usually represented in CGE models as an extended emissions-trading system (ETS) where developing countries receive emissions permits in proportion to their business-as-usual levels and engage in trade with industrialized countries. By non-arbitrage, CDM then leads to a full equalization of marginal abatement costs across all sectors in the industrialized and the developing country (at the level of the endogenous permit price).

Representing the CDM as an extended ETS has three major shortcomings. First, it may overstate the cost-saving potential of the CDM. As a project-based mechanism the CDM is unlikely to capture all the cost-effective abatement options in production and consumption that would be realized under an ETS. Springer (2003) therefore describes this modeling approach as an optimistic version of the CDM. Addressing this issue, the EMF-16 analyses of the economic and energy sector impacts of the Kyoto Protocol (Weyant and Hill, 1999) constrain the sale of CDM credits to 15% of the permit sales that would result under a full global emissions trading scheme. In this context, Manne and Richels (1999) issue the caveat that the percentage-constraint used is a highly subjective estimate meant to capture difficulties in the implementation of the CDM (see also Bernstein et al., 1999, and MacCracken, 1999).⁵

⁵ Another rather political than technical reasons for constraining the trade of emissions allowances between Annex I and non-Annex I countries is to represent the supplementarity requirement laid out in the Marrakech Accords to the Kyoto Protocol. Those accords state that the use of each of the flexible mechanisms (ETS, CDM, JI) shall be supplemental to domestic action and that domestic action shall thus constitute a significant effort made by each Party included in Annex I to meet its quantified emission limitation and reduction commitments. Supplementarity constraints form part of various national climate policy strategies such as the EU Climate Action and Renewable Energy Package (EU, 2008).

Second, the CDM representation as an ETS is inconsistent with the incentive structure of the CDM: Firms undertaking CDM projects are compensated for employing less emissions-intensive but more expensive production technologies through the sale of CERs. In contrast, in an ETS, firms face an emissions price on their inputs which increases their costs and decreases their market shares, while the revenues from CERs accrue to the region's representative agent or government. Representing the CDM as a form of ETS therefore leads to inconsistent sector-level impacts, including sectoral prices, production, and trade flows.

Finally, representing the CDM as an ETS does not accommodate the CDM decision framework of the primary CDM market which entails an investment decision by those Annex I countries intending to buy CERs.⁶ In an ETS modeling framework the overall level of emissions reductions is the decision variable which endogenously yields the carbon price and permit-trade volumes. While this framework may accommodate the price-forming mechanism of the observable secondary CER market, it cannot capture the fundamental investment decisions that lead to the CDM project development in the contractual primary CER market.

3. An incentive-compatible CGE modeling framework for the CDM

Our CGE modeling approach addresses the above-mentioned shortcomings by representing the CDM in an incentive-compatible manner. For that purpose, we adopt two key ideas of the CDM. First, firms will only engage in the CDM if they do not lose, suggesting that while they use more energy-efficient (and more expensive) production techniques, the firms are compensated such that their net production costs are unchanged. Second, CDM projects are bilateral agreements about "how much money" rather than about "how much carbon", i.e. countries demanding CDM credits decide on the amount of their CDM investment and understand the CDM credits as an (endogenous) outcome of that investment. This modeling approach allows for a microconsistent assessment of the CDM impacts at the sector and economy-wide level.

We illustrate the CGE implementation of our approach within a stylized multi-region model of the global economy which can easily be adapted to more complex structures (see section 4 for a more elaborate large-scale implementation and application). A comprehensive algebraic model formulation is provided in Appendix A. Here we focus on the equilibrium conditions that are required for the incentive-compatible representation of the CDM. In the stylized model, macroeconomic production in each region takes place with inputs of capital, labour, and energy where the Cobb-Douglas composite of capital and labor trades off with energy at a constant elasticity of substitution (CES). We focus on a single sector-representing firm.

The default unit-cost function of the representative firm (sector) without CDM is given by:

⁶ In general, CDM buyers have two markets in which to purchase CERs, the primary and the secondary market (see, e.g., World Bank, 2005; Green, 2008). In the primary market, the investor and project developer agree on a price for the expected future credits from a CDM project. The resulting contract, which is known as an Emissions Reduction Purchase Agreement (ERPA), is similar to a project-finance agreement and can vary from case to case. The secondary CER (sCER) market is used for trading credits which are already delivered or with a guarantee of delivery or compensation if the contract is broken. In contrast to the primary market, the secondary one has an observable price (which is higher than the price in the primary CER market due to lower risks for the buyer).

$$C(p_E, p_L, p_K) = (\theta_E p_E^{1-\sigma} + (1 - \theta_E (p_K^\vartheta p_L^{1-\vartheta})^{1-\sigma})^{\frac{1}{1-\sigma}}) \quad (1)$$

where p_E, p_L, p_K denote the prices of energy, labour, and capital, respectively; θ_E the value share of energy inputs, ϑ the value share (output elasticity) of capital, and σ the elasticity of substitution between energy and the capital–labor composite.

CDM investments in the hosting representative firm (sector) can be represented as a combination of sectoral output subsidies and shadow emission taxes. The shadow emission taxes induce the adoption of more energy-efficient and more expensive production technologies, while the output subsidies compensate the representative firm in the CDM-hosting sector for the increase in production costs. Denoting the emission tax with τ and the output subsidy with μ , the unit-cost function of the firm adopting CDM becomes:⁷

$$C(\mu, \tau, p_E, p_L, p_K) = \frac{1}{1 + \mu} (\theta_E (p_E (1 + \tau))^{1-\sigma} + (1 - \theta_E (p_K^\vartheta p_L^{1-\vartheta})^{1-\sigma})^{\frac{1}{1-\sigma}}) \quad (2)$$

Incentive compatibility implies that the CDM-hosting firm does not increase its cost of production. The arbitrage condition thus reads as:

$$C(\mu = 0, \tau = 0, p_E, p_L, p_K) \geq C(\mu, \tau, p_E, p_L, p_K) \quad (3)$$

The absolute level of CDM investment which, in our approach, is exogenously chosen by the CDM donor country (demanding CDM emissions offsets) provides the CDM budget constraint. The CDM-investment transfer must cover the difference between subsidy payments and the implicit revenues from the shadow emission tax:

$$p_L T \geq \mu p_Y Y - \tau p_E E \quad (4)$$

where p_Y and Y denote the price and quantity of output, p_E and E the price and quantity of energy. We use p_L as a numéraire that translates the nominal CDM transfer level T into real terms.

The incentive-compatible CDM-modeling approach described above differs in several respects from the commonly used ETS representation.⁸ In particular, the incentive-compatible CDM formulation is associated with a lower economic efficiency of reducing emissions than the ETS representation. In general, emissions reductions can take place through fossil-fuel switching, improving energy efficiency, and reducing output. However, the option for curbing emissions through output reduction in emission-intensive sectors of the CDM host country vanishes in our incentive-compatible CDM representation due to the introduction of output subsidies. Second, the participating firm (sector) in the CDM host country does not suffer from an increase in its production cost. Third, CDM transfers do not enter the budget of the representative agent in the CDM host country (as they are used to compensate CDM participating sectors via output subsidies). Finally, in contrast to the ETS representation, there

⁷ In the mixed complementarity formulation of our equilibrium model, this arbitrage condition is associated with the endogenous subsidy rate μ .

⁸ The unit-cost function of the ETS-type CDM representation is equivalent to Eq. (2) with the output subsidy rated set to zero ($\mu = 0$) and with the shadow emission price (τ) determined by the emission cap of the multi-region ETS which includes the CDM hosting countries.

is no trade-induced price equalization of emission prices in the CER demanding country (the CDM donor) and the prices for CDM offsets in the CDM host country.

4. Model application

We highlight the relevance of our novel CDM representation by means of a large-scale CGE application based on empirical data. For this purpose, we adopt a generic multi-region, multi-sector CGE model of global trade and energy use (see, e.g., Böhringer and Rutherford, 2002) calibrated to data of the Global Trade Analysis Project (GTAP). We compare the economic impacts from the CDM when represented either in our novel incentive-compatible approach or in the conventional ETS manner. We first provide a non-technical summary of the basic model structure,⁹ followed by information on the underlying GTAP database. We then lay out the policy scenarios and simulation results (including sensitivity analysis for key parameters).

4.1. Model structure

Goods are produced with inputs of intermediate goods and primary factors (skilled labor, unskilled labor, capital, and natural resources). Primary energy goods (crude oil, natural gas, and coal) exhibit decreasing returns to scale with respect to natural resource inputs which are sector-specific. Capital and labor are intersectorally mobile, but immobile across regions.

The production of energy and other goods is described by nested constant-elasticity-of-substitution (CES) production functions which characterize substitution possibilities between inputs (see Figure 1).

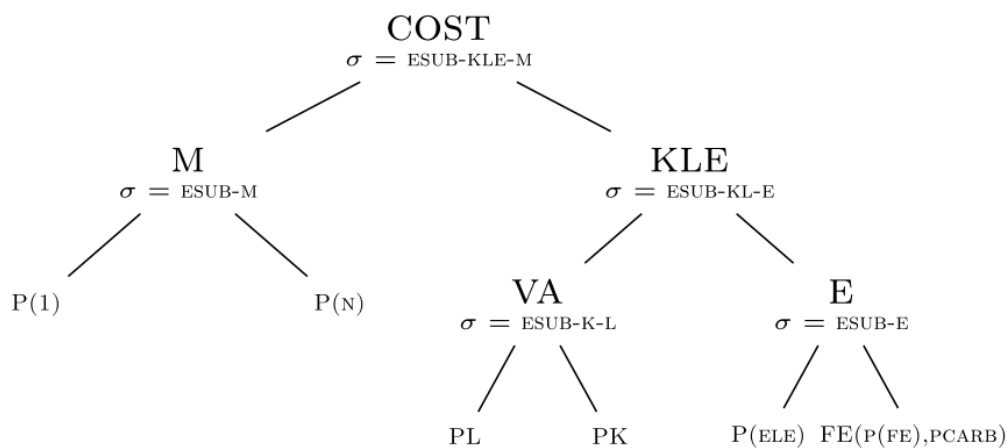


Figure 1. Nesting structure of CES production functions (except for fossil fuels).

For all goods except fossil fuels, the CES production functions are arranged in three levels. The top-level nest combines an aggregate of capital, labor, and energy inputs (KLE) with a composite of material inputs (M); the second-level nest combines an aggregate of energy inputs (E) with a value-added composite of capital and labor inputs (VA) in the KLE-nest, as well as non-energy material inputs (P(1) to P(N)) in the M-nest; and the third level captures

⁹ A more detailed technical description is provided in Böhringer and Rutherford (2011).

the substitution possibilities between capital (PK) and labor (PL) in the VA-nest, and the composition of the different final-energy inputs (coal, refined oil, gas) (P(FE)) and their associated CO₂ emissions (PCARB) in the FE-nest. The production of fossil fuels combines sector-specific fossil-fuel resources with an aggregate of all other inputs which enter in fixed proportions.

The representation of international trade follows Armington's (1969) approach of differentiating goods by country of origin. Thus, goods within a sector and region are represented as a CES aggregate of domestic goods and imported ones with associated transport services. Final consumption in each region is determined by a representative agent who maximizes consumptions subject to its budget constraint. Consumption is represented as a CES aggregate of non-energy goods and energy inputs and the budget constraint is determined by factor and tax incomes with fixed investment and public expenditure.

4.2. Database and aggregation

The model is calibrated to the database version 7.1 of the Global Trade Analysis Project (GTAP). This database represents production, consumption, trade and CO₂ emissions from fossil fuel combustion for 113 countries/regions, 57 commodities and 5 primary factors for the benchmark year 2004 (Narayanan and Walmsley, 2008). Table C1 in the appendix provides an overview of the key elasticities used for our model parameterization.

For our economic impact assessment of the CDM, we aggregate the GTAP regions into two blocks: Annex I (AN1) countries which can invest in CDM projects and non-Annex I (NA1) countries which can implement CDM projects. With respect to commodities, the aggregation includes the aforementioned five energy commodities (coal, natural gas, crude oil, refined oil, and electricity), an energy-intensive composite (consisting of the GTAP sectors non-ferrous metals, non-metallic minerals, iron and steel, and chemical products), an aggregate transport good, and a composite of all other remaining goods and services.

4.3. Model scenarios

We devise three model scenarios to illustrate the quantitative effects of applying the incentive-compatible CDM framework in numerical modeling studies. Those are a reference cap-and-trade scenario in which Annex I countries reduce their emission without using the CDM, the commonly applied ETS representation of the CDM, and our alternative incentive-compatible CDM representation.

The reference cap-and-trade scenario (**REF**) is designed as a ballpark characterization of current and contemplated climate policies. In the reference cap-and-trade (REF) scenario Annex I countries reduce their CO₂ emissions by 20% with respect to the benchmark year of 2004. This magnitude is indicative of possible short to medium-term emissions reductions (Levin and Bradley, 2010) and broadly in line with the pledges submitted to the Copenhagen Accord which followed the 15th Conference of the Parties to the UNFCCC.

Under the incentive-compatible CDM scenario (**CDM**) Annex I countries can invest in CDM projects in non-Annex I countries and relax their domestic emissions target by the emissions reduced due to these projects. We determine the optimal level of CDM investment by iteratively optimizing the amount of CDM transfers with respect to its effect on Annex I countries' welfare. This ensures comparability to the commonly applied ETS representation

of the CDM in which the level of CDM investment is endogenously determined.

The ETS representation of the CDM models the CDM as an integrated emissions-trading system (IET) (see, e.g., Springer, 2003, Burniaux et al., 2009). Annex I countries are subjected to the same 20% emissions-reduction target as in the REF scenario, but they are now allowed to trade emission permits with non-Annex I countries which are allocated their benchmark(-2004) emissions.

To date, more than two thirds of all CDM projects have been implemented in the renewable energy sector (UNEP Risoe, 2012).¹⁰ We approximate this distribution within our aggregation by allowing CDM implementation in the electricity sector only. Likewise, the IET representation of the CDM is limited to the electricity sector.

We design the comparison between CDM and IET as a cost-effectiveness analysis in which global emissions are held constant at the reference scenario level. This allows for a consistent welfare comparison without the need to assess the monetary benefits of emissions reductions.

4.4. Results

Figure 2 displays the welfare effects across our three core scenarios in terms of percentage changes in Hicksian equivalent variation of income. The reference cap-and-trade (REF) scenario results in welfare reduction in both Annex I and non-Annex I countries. The introduction of carbon pricing in Annex I countries in that scenario increases domestic prices. This reduces consumption in Annex I countries and affects non-Annex I countries through reduced import demand and increased export prices.

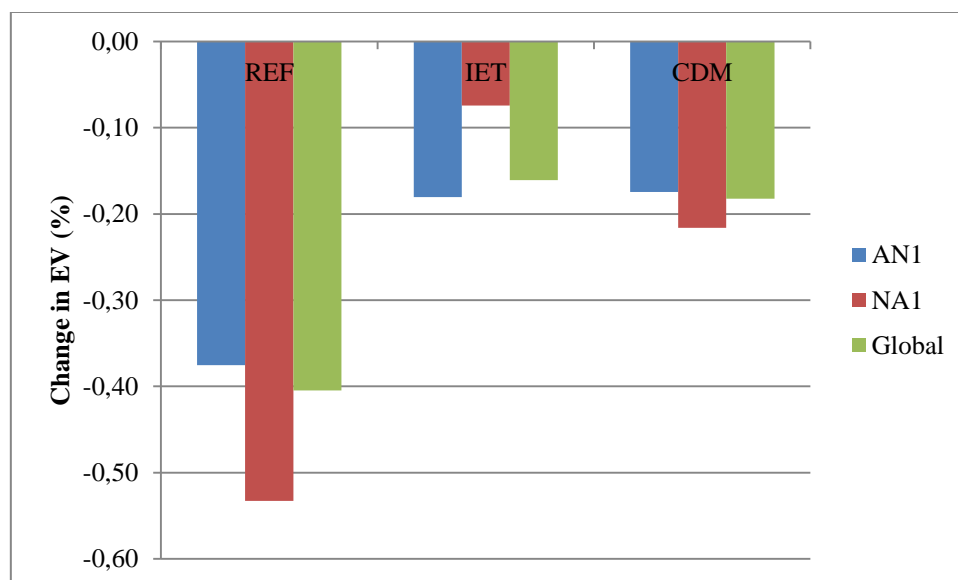


Figure 2. Changes in Hicksian equivalent variation of income.

¹⁰ Detailed information on the type of CDM projects can be found at <http://www.cdmpipeline.org/cdm-projects-type.htm> (accessed 05/27/ 2012).

Allowing Annex I countries to meet part of their emissions-reduction target by purchasing CDM emissions offsets in the IET and CDM scenarios alleviates part of the negative welfare effects of the reference scenario. Both scenarios lead to similar relative welfare gains of 52-60% for Annex I countries and globally. However, their effect on non-Annex I countries differs significantly. The IET representation of the CDM yields large relative welfare improvements of 86% for non-Annex I countries, while the incentive-compatible CDM representation yields improvements of 59%. Compared across regions, the incentive-compatible CDM representation preserves the distribution of welfare impacts between Annex I and non-Annex I countries, while the IET representation leads to disproportionately more welfare gains for non-Annex I countries than for Annex I countries.

The relative welfare gains of the IET and CDM scenarios emerge from increased where-flexibility of emissions reduction through CDM offsets. Table 1 provides an overview of the key characteristics of the CDM for both model scenarios. The IET scenario induces CDM transfers from Annex I to non-Annex I countries (in the form of payments for emissions allowances) of USD 17.6 billion, which yields emissions offsets of about 1.2 GtCO₂ for Annex I countries. Consequently, more than half of Annex I countries' emissions-reduction commitment is met through CDM emissions permits. As a result of the inflow of emissions permits, the price of carbon in Annex I countries decreases by 60%, from 36 USD/tCO₂ to 14.5 USD/tCO₂.

In comparison, the CDM scenario induces 35% less CDM transfers to non-Annex I countries (USD 11.5 billion), which yield 9% less emissions offsets for Annex I countries (1.1 GtCO₂). Again, about half of Annex I countries' emissions-reduction commitment is met through the CDM. The price of carbon in Annex I countries decreases by 58%, i.e., two percent less than in the IET scenario. While the carbon price in the ETS representation is the same as the CER price, the CDM scenario allows for price differentiation. In the CDM scenario, the CER price (established by the ratio of CDM investment to non-Annex I countries' emissions reductions brought about by the investment) amounts to 10.4 USD/tCO₂ which is 32% lower than the price of carbon in Annex I countries (established through a domestic ETS) in that scenario.

Table 1. Overview of CDM-specific results

Parameter	Unit	REF	IET	CDM
P(CO ₂) in AN1	(USD/tCO ₂)	36,3	14,5	15,3
P(CER) from NA1	(USD/tCO ₂)	0,0	14,5	10,4
CDM transfers	(billion USD)	0,0	17,6	11,5
CDM offsets	(GtCO ₂)	0,0	1,2	1,1
ΔEmissions(AN1)	(%)	-20,0	-9,5	-10,3
ΔEmissions(NA1)	(%)	4,0	-9,1	-8,1
ΔEmissions(Total)	(%)	-9,3	-9,3	-9,3

Figure 3 illustrates the differences between the IET and CDM scenario at the sector level. It highlights the price and output changes in the CDM-implementing electricity sector for the two scenarios (with respect to the reference cap-and-trade scenario). In the IET scenario, electricity prices in non-Annex I countries increase by 16.5% as a result of emissions pricing

in the sectoral ETS implementation. As a consequence, electricity output falls by 9.2% in non-Annex I countries. At the same time, Annex I countries expand their output by 4.9% due the decrease in their domestic price of carbon.

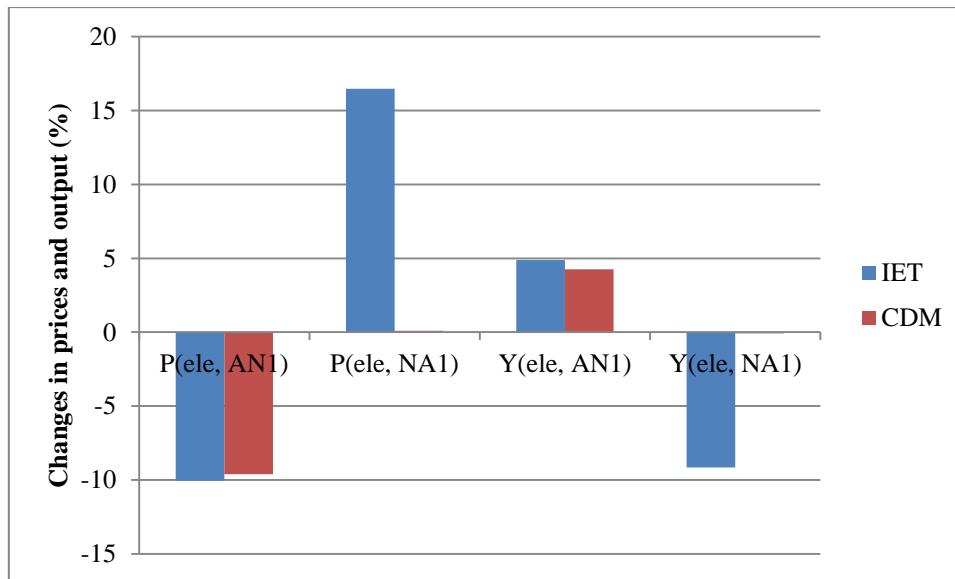


Figure 3. Percentage output and price changes (compared to the REF scenario) in the electricity sector in Annex I (AN1) and non-Annex I (NA1) countries.

The CDM scenario yields qualitatively different results compared to those of the IET scenario. The prices and output of the CDM-implementing electricity sector remain constant in the CDM scenario, which reflects the CDM incentive-compatibility condition that keeps the firm's unit cost of production unchanged from its reference level. Annex I countries' output is influenced by their comparatively slighter decrease in carbon prices relative to the IET scenario. As a result, the increase in Annex I countries' electricity output is 0.6% lower in the CDM scenario compared to the IET one.

4.5. IET scenario with rebates

The inconsistent sectoral impacts of the CDM in the IET scenario may be alleviated by changing the scenario's incentive structure. Instead of representing the sector-level CDM incentive structure through the auctioning of emissions permits in the IET scenario, we consider a rebating scheme (**IET_rb**) in which the sector participating in the CDM is compensated for the direct cost of emissions permits through output-based rebates. This modification differs from the incentive-compatible CDM formulation, because the sector participating in the CDM is not compensated to the extent that its unit costs of production are held constant at their reference level.

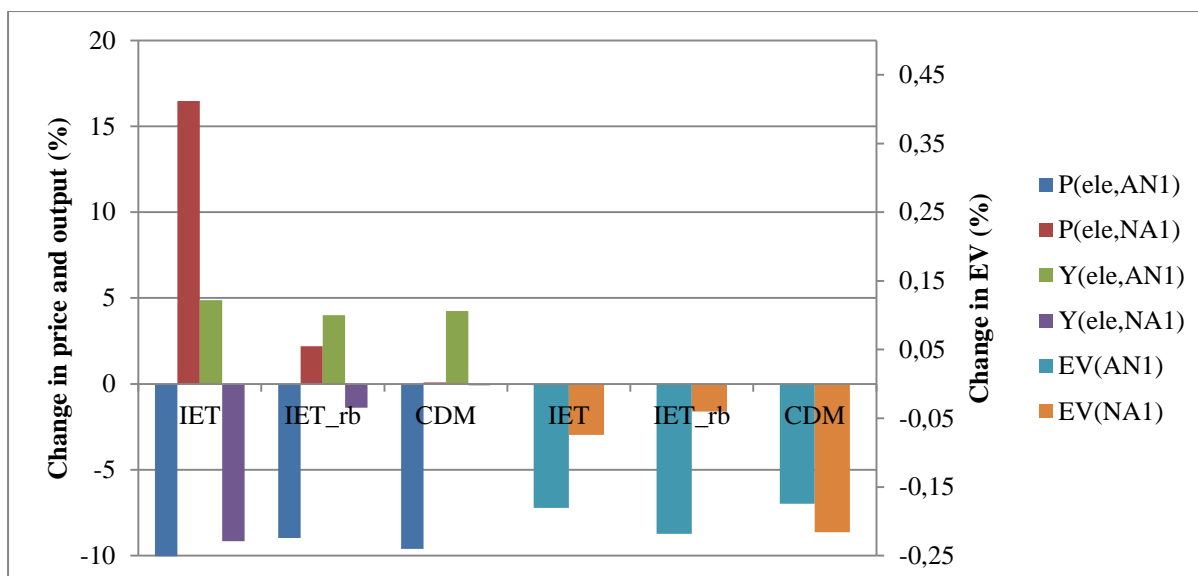


Figure 4. Comparison sector-level impacts (left axis) and welfare effects (right axis) of an alternative ETS representation with rebates (IET_rb) to the standard ETS representation of the CDM (IET) and the incentive-compatible framework (CDM); the basis of comparison is the REF scenario.

Figure 4 contrasts the sector-level effects and overall welfare impacts of the alternative ETS representations (IET_rb) with the incentive-compatible CDM scenario (CDM) and the standard ETS representation (IET). The figure indicates that compared to the standard ETS representation, the price increases and output losses in the CDM-implementing electricity sector are significantly reduced in the alternative representation, from 16.5% to 2.2% and from -9.2% to about -1.4% respectively. However, the directional impacts still contrast with, and are opposed to, the price and output changes in the incentive-compatible CDM representation.

In addition, the welfare differences between the scenarios show further divergences. In the ETS representation with rebates, the welfare losses for Annex I countries increase by 21% and those for non-Annex I countries decrease by 46% compared to the standard ETS representation.¹¹ This widens the difference of welfare effects to the incentive-compatible CDM scenario. The ETS representation with rebates may therefore further overestimate the potential gains that are achievable through the CDM in non-Annex I countries compared to the standard ETS representation.

4.6. Sensitivity analysis

We assess the robustness of our findings with respect to changes in key model parameters. Those are the fossil-fuel supply elasticities, the Armington trade elasticities, and the emissions-reduction target. In our piecemeal sensitivity analysis we double (x2) or halve (:2) the fuel-supply (*esub_ff*) and Armington trade elasticities (*esub_arm*) respectively;

¹¹ Reasons for the effect on Annex I countries are that the CDM becomes less efficient with rebates granted to the electricity sector, as those stand in the way of greater emissions reductions. Reasons for the effects on non-Annex I countries are found on the sector level as consumers in non-Annex I countries benefit from less drastic price increases for electricity compared to the standard representation.

concerning emissions reductions (*emicut*), we change the central-case target for Annex I countries from 20% to 10% and 30% respectively.¹²

In general, decreasing the fossil-fuel supply elasticities reduces the responsiveness of the fossil-fuel supply to demand reductions in the emissions-abating Annex I countries, so that non-Annex I countries absorb the excess supply. Higher Armington elasticities increase the trade response to changes in prices and therefore accentuate the competitive disadvantages of energy-intensive industries which operate in carbon-pricing Annex I countries. Thus, reducing the fossil-fuel supply elasticities and increasing the Armington elasticities are generally associated with additional welfare losses in Annex I countries and relative welfare gains in non-Annex I countries. Increasing the stringency of Annex I countries' emissions-reduction targets is associated with a greater economic burden for those countries, but also for non-Annex I countries due to reductions in import demand and increases in export prices in Annex I countries.

Table 2. Sensitivity analysis in terms of relative percentage changes in welfare (EV) and electricity output (Y(ele)) between IET and CDM scenarios.

Scenarios modifications	$\Delta EV(\text{IET}) - \Delta EV(\text{CDM})$		$\Delta Y(\text{ele}, \text{IET}) - \Delta Y(\text{ele}, \text{CDM})$	
	AN1	NA1	AN1	NA1
main	-0,006	0,142	0,631	-9,071
<i>esub_ff</i> : 2	0,000	0,139	0,788	-9,486
<i>esub_ff</i> x 2	-0,011	0,142	0,489	-8,608
<i>esub_arm</i> : 2	-0,033	0,297	0,870	-8,795
<i>esub_arm</i> x 2	0,012	0,056	0,640	-9,254

Table 2 indicates that the relative welfare and sector-level differences between the IET scenario and the CDM one are preserved for a wide range of elasticity parameters. The alternative parameter assumptions result in variations around the main scenarios' values with the following trends. First, halving the Armington elasticities increases the relative welfare differences between the IET and CDM scenarios for Annex I and non-Annex I countries (and vice versa). Second, changes in the fossil-fuel supply elasticities have little effect on the relative welfare differences between the model scenarios. Third, the negative output effects in the CDM-implementing sector are preserved in the IET scenarios under all scenario modifications.

Figure 5 focuses on the welfare effects of different emissions reduction targets. Similar welfare effects are obtained in both CDM representations when Annex I countries adopt a low emissions reduction target of 10%. However, a high emissions reduction target of 30% yields qualitatively different results for each representation, in particular for non-Annex I countries. The incentive-compatible CDM representation maintains the distribution of

¹² An emissions reduction target by Annex I countries of 10% is broadly in line with the Kyoto Protocol's initial emissions reduction target of 5.2% below 1990 levels (which correspond to reducing emissions by about 10% below 2004 levels). A target of 30% is closer to the range of emissions reductions (25% to 40% below 1990 levels) that are needed to stabilize global emissions at 450 ppm (see, e.g., Levin and Bradley, 2010).

welfare impacts between Annex I and non-Annex I, while the ETS representation is associated with large welfare gains for non-Annex I countries which exceed the no-policy baseline level. Thus, while using an ETS representation of the CDM may be justified for analysing the macroeconomic impacts of low emissions reduction targets, it can significantly distort the analysis for stringent targets. No short-cut representation can be used for a sector-level analysis, as the sectoral impacts of the ETS and CDM representations remain highly differentiated for each emissions reduction target.¹³

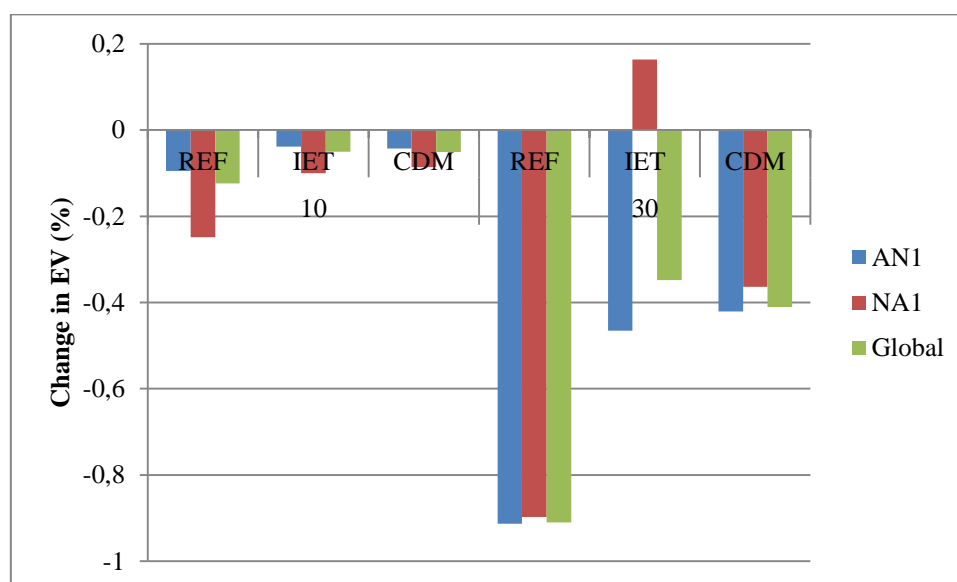


Figure 5. Sensitivity analysis with respect to welfare impacts for emissions reduction targets in Annex I countries of 10% and 30%.

5. Conclusion

The Kyoto Protocol, and with it the CDM, will enter its second, 7-year long commitment phase in 2013. In the next years, Annex I countries will therefore be able to continue to meet part of their domestic emissions reduction commitments through CDM investments and the resulting CDM emissions credits. This situation demands a consistent CDM modeling approach to account for this possibility and to compare the CDM to alternative policy options, such as the sectoral or full linking of emissions-trading systems between industrialized and developing countries.

This study presents an incentive-compatible CDM modeling approach that is meant to facilitate a consistent analysis of CDM effects and interactions within CGE models. The approach is based on two tenets. First, the firms implementing CDM projects are compensated for the greater costs of reducing emissions in such a way that their unit costs of production remain unchanged. Second, the countries demanding CDM-emissions offsets decide on the amount of CDM investment and receive emissions offsets as a return to that investment.

¹³ The relative output changes between the IET and CDM scenarios in the CDM-implementing sector in non-Annex I countries (as defined in Table 2) are -4.1% and -14.4% for a 10% and 30% emissions-reduction target, respectively.

A comparison with the common modeling approach of representing the CDM as an asymmetric ETS (in which CDM host countries are allocated their benchmark emissions) shows several divergences. At the sector level, the ETS representation of the CDM results in increased prices in the CDM-implementing non-Annex I sector, which leads to decreases in output and exports. In contrast, prices and output in the CDM-implementing non-Annex I sector remain roughly constant in the incentive-compatible CDM approach. While the domestic Annex I carbon prices equalize with the price of CDM offsets in the ETS representation, the incentive-compatible CDM framework allows for price differentiation between the two prices. The study's results which indicate that CDM-offset prices are lower than the price of emissions allowances in Annex I countries is in line with market observations, e.g., those of the European Union Emission Trading Scheme (EU ETS) in which similar price differentiations have emerged.

There are also distinct differences between the incentive-compatible CDM framework and the ETS representation on the macroeconomic level. In particular, the welfare improvements for non-Annex I countries are less drastic in the incentive-compatible framework as in the ETS representation, since CDM transfers are used in the former to compensate the firm/sector which is implementing CDM projects. This contrasts with the ETS representation which maximizes consumption from the incoming revenues from the trade in emissions permits.

The incentive-based CDM approach presented in this study yields several CDM-specific effects, such as price differentiation and sectorally consistent price and output effects which the common ETS representation of the CDM is unable to account for. In addition, it allows for economic comparisons to policies involving sectoral emissions trading between industrialized countries and developing ones, something which is hardly possible when the CDM is represented as an ETS itself.

Despite of its advancements there are various aspects of the CDM which our incentive-based CDM representation still abstracts from. First, we request that CDM hosting firms (sectors) must be compensated at their pre-CDM (reference) cost level. However, CDM hosting firms might try to bargain for positive profits with CDM donors on the distribution of overall cost savings from CDM (this would essentially call for a game-theoretic setting). Second, the top-down characterisation of sector-specific production possibilities through continuous functional forms cannot address the project-level characteristics of CDM but describes a sectoral CDM policy (to capture discrete projects one would have to include bottom-up activity analysis in the top-down CGE framework). Third, the representation of the CDM market is relatively crude and, while focussing on the primary CDM market, it does not make a distinction between the primary and secondary CDM market.

We defer appropriate extensions to future research. We finally note that while our modeling approach has been analyzed and presented with reference to the CDM, it can be generalized to other related issues, such as the impacts of climate finance and green growth strategies.

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Appendix A. Algebraic model summary

Following Mathiesen (1985), Cottle and Pang (1992) and Rutherford (1995), an economic equilibrium can be expressed as a mixed complementarity problem where inequalities are associated with decision variables. The inequalities correspond to the two classes of conditions associated with a general equilibrium: (i) exhaustion of product (zero profit) conditions for constant-returns-to-scale producers, and (ii) market clearance for all goods and factors. The former class determines activity levels, and the latter determines price levels. In equilibrium, each of these variables is linked to one inequality condition: an activity level to

an exhaustion of product constraint and a commodity price to a market clearance condition. Furthermore, income balances keep economic agents on their budget lines. In the following, we state the equilibrium conditions for our stylized CGE model of section 3. Tables A1-A5 provide an overview of the symbols and notation used. For a convenient calibration of functional forms based on an initially balanced dataset we make use of the calibrated share form (see Böhringer et al., 2003). Numerically, the model is implemented in the general algebraic modeling system GAMS (Brooke et al., 1996) and solved using PATH (Dirkse and Ferris, 1995).

Zero-profit conditions:

1. Macro output:

$$\left(\theta_r^E (p_r^{ED} (1 + \tau_r))^{1-\sigma} + (1 - \theta_r^E) (v_r^{\theta_r^K} w_r^{(1-\theta_r^K)})^{1-\sigma} \right)^{\frac{1}{1-\sigma}} \geq p_r^Y (1 + \mu_r) \quad \perp \quad y_r \quad (5)$$

2. Energy:

$$(\theta_r^R v_r^{1-\eta} + (1 - \theta_r^{ER}) q_r^{1-\eta})^{\frac{1}{1-\eta}} \geq p^E \quad \perp \quad y_r^E \quad (6)$$

3. Energy demand:

$$p^E + p^{CO_2} \geq p_r^{ED} \quad \perp \quad y_r^{ED} \quad (7)$$

4. Armington aggregate (in final consumption):

$$\left(\sum_s \theta_{sr}^Y p_r^{1-\gamma} \right)^{\frac{1}{1-\gamma}} \geq p_r^A \quad \perp \quad y_r^A \quad (8)$$

5. Welfare (utility):

$$w_r^{\theta_r^{LW}} p_r^{A(1-\theta_r^{LW})} \geq p_r^W \quad \perp \quad y_r^W \quad (9)$$

Market-clearing conditions:

6. Output:

$$Y_r \geq \sum_s \bar{c}_{rs} A_s \left(\frac{p_s^A}{p_r^Y} \right)^\gamma \quad \perp \quad p_r^Y \quad (10)$$

7. Energy:

$$\sum_r y_r^E \geq \sum_r y_r^{ED} \quad \perp \quad p^E \quad (11)$$

8. Energy demand:

$$y_r^{ED} \geq \overline{ed}_r y_r \left(\frac{(1 + \mu_r) p_r^Y}{(1 + \tau_r) p_r^{ED}} \right)^\sigma \perp p_r^{ED} \quad (12)$$

9. Labor:

$$\overline{L}_r \geq \overline{ls}_r \frac{y_r^W p_r^W}{w_r} + \overline{l}_r y_r \left(\frac{p_r^Y (1 + \mu_r)}{v_r^{\theta_r^K} w_r^{1-\theta_r^K}} \right)^\sigma \frac{v_r^{\theta_r^K} w_r^{(1-\theta_r^K)}}{w_r} \perp w_r \quad (13)$$

10. Capital:

$$\overline{K}_r \geq \overline{f}_r y_r^E \left(\frac{p_r^E}{v_r} \right)^\eta + \overline{k}_r y_r \left(\frac{p_r^Y (1 + \mu_r)}{v_r^{\theta_r^K} w_r^{1-\theta_r^K}} \right)^\sigma \frac{v_r^{\theta_r^K} w_r^{(1-\theta_r^K)}}{v_r} \perp v_r \quad (14)$$

11. Fossil-fuel resources:

$$\overline{Q}_r \geq \overline{Q}_r y_r^E \left(\frac{p_r^E}{q_r} \right)^\eta \perp q_r \quad (15)$$

12. Armington:

$$\sum_s c_{sr} y_r^A \geq \sum_s c_{sr} y_r^W \frac{p_r^W}{p_r^A} \perp p_r^A \quad (16)$$

13. Welfare:

$$y_r^W \left(\sum_s c_{sr} + \overline{ls}_r \right) \geq \frac{RA_r}{p_r^W} \perp p_r^W \quad (17)$$

14. Emissions (applies to emissions-regulating regions only):

$$\overline{CO}_2 \geq \sum_r y_r^{ED} \perp p^{CO_2} \quad (18)$$

Constraints:

15. Emissions (applies to emissions-regulating regions only):

$$\overline{CO}_{2r} CO_{2r} \geq y_r^{ED} \perp CO_{2r} \quad (19)$$

16. CDM incentive compatibility:

$$\begin{aligned} & (\theta_E (p_E)^{1-\sigma} + (1 - \theta_E (p_K^\vartheta p_L^{1-\vartheta})^{1-\sigma})^{\frac{1}{1-\sigma}} \\ & \geq \frac{1}{1 + \mu} (\theta_E (p_E (1 + \tau))^{1-\sigma} + (1 - \theta_E (p_K^\vartheta p_L^{1-\vartheta})^{1-\sigma})^{\frac{1}{1-\sigma}} \\ & \perp \mu_r \end{aligned} \quad (20)$$

17. CDM budget balance:

$$\mu_r p_r^Y y_r - \tau_r p^E y_r^{ED} \geq w_r \sum_s T_{sr} \perp \tau_r \quad (21)$$

Income balance:

$$RA_r = \bar{Q}_r q_r + \bar{K}_r v_r + \bar{L}_r w_r + p^{CO_2} \bar{CO}_{2r} CO_{2r} + w_r \sum_s T_{sr} - \sum_s w_s T_{rs} + \tau_r y_r^{ED} p_r^{ED} - \mu_r y_r p_r^Y \perp RA_r \quad (22)$$

Table A1. Activity variables

y_r	Aggregate production in region r
y_r^E	Energy supply in region r
y_r^{ED}	Energy demand in region r
y_r^A	Armington aggregate in region r
y_r^W	Welfare in region r

Table A2. Price variables

p_r^Y	Price of aggregate output in region r
p^E	Price of energy
p_r^{ED}	Price of energy demand in region r
w_r	Wage rate in region r
v_r	Return to capital in region r
q_r	Rent to natural resources in region r
p_r^A	Price of Armington good in region r
p_r^W	Welfare price
p^{CO_2}	Price of emissions permits

Table A3. Additional variables

CO_{2r}	CO ₂ emissions in regions r
RA_r	Income level of representative agent in region r
μ_r	CDM incentive subsidy
τ_r	CDM emissions tax
T_{sr}	Value of CDM purchases

Table A4. Cost shares

θ_r^E	Benchmark cost share of energy in aggregate output in region r
θ_r^K	Benchmark share of capital in value-added composite in region r
θ_r^R	Benchmark share of specific resource in energy production in region r
θ_{sr}^Y	Benchmark share of output from region s in consumption composite of region r
θ_r^{LW}	Benchmark share of leisure in welfare composite in region r

Table A5. Endowments

\overline{L}_r	Labor endowment in region r
\overline{ls}_r	Benchmark leisure demand in region r
\overline{l}_r	Benchmark labor demand in region r
\overline{K}_r	Capital endowment in region r
\overline{f}_r	Benchmark capital demand in the energy nest in region r
\overline{k}_r	Benchmark capital demand in the output nest in region r
\overline{Q}_r	Resource endowment in region r
$\overline{CO_2}$	Emissions target
\overline{c}_{rs}	Benchmark bilateral trade flows
\overline{ed}_r	Benchmark energy demand in region r

Table A6. Elasticities

σ	Substitution between energy inputs and the capital-labor composite
η	Substitution between capital and resources in the energy nest
γ	Substitution between the import aggregate and the domestic input

Appendix B. GAMS/MPSGE code of stylized CGE model

```

$title Illustrative CGE Model of Incentive-Compatible CDM at the Sector Level
set r Regions /oecd,china,row/;

alias (r,rr);

parameter
  c0(r,rr) Consumption (=trade matrix),
  ls0(r) Leisure demand,
  le0(r) Labor + leisure endowment,
  ke0(r) Capital endowment,
  r0(r) Resource endowment,
  y0(r) Output,
  l0(r) Labor demand,
  k0(r) Capital demand,
  f0(r) Capital demand,
  es0(r) Energy supply,
  ed0(r) Energy demand,

  evs(r) Energy value share,
  kvs(r) Capital value share,
  sigma Cross-price elasticity of energy demand /0.5/,
  eta Cross-price elasticity of energy supply /0.5/,
  gamma Cross-price elasticity in consumption demand /4/,

  cdmv(r,rr) Value of CDM purchases,

```

```

elim(r)      Emissions limit,
target       Emissions target /0/;

```

```

table      bmkdata(*,r)      Stylized benchmark data
           oecd      china      row
y0         100         40         50
evs        0.05        0.08        0.12
kvs        0.40        0.50        0.40
zeta       1.75        1.25        1.25
es0        0.4         0.1         0.5
dvs        0.8         0.9         0.6;

```

```

evs(r) = bmkdata("evs",r);
y0(r)  = bmkdata("y0",r);
ed0(r) = evs(r)*y0(r);
es0(r) = bmkdata("es0",r)*sum(rr,ed0(rr));

```

```

f0(r)  = 0.5*es0(r);
r0(r)  = 0.5*es0(r);
kvs(r) = bmkdata("kvs",r);
k0(r)  = kvs(r) * (y0(r)-ed0(r));
ke0(r) = f0(r) + k0(r);
l0(r)  = y0(r)-ed0(r)-k0(r);
ls0(r) = 0.5 * l0(r);
le0(r) = l0(r) + ls0(r);
cdmv(r,rr) = 0;

```

```

c0(r,r) = bmkdata("dvs",r)*(le0(r)-ls0(r)+ke0(r)+r0(r));

```

```

parameter      mchk;
mchk(r,"d0") = c0(r,r);
mchk(r,"m0") = le0(r)-ls0(r)+ke0(r)+r0(r) - c0(r,r);
mchk(r,"x0") = y0(r)-c0(r,r);
mchk("total","d0") = sum(r,c0(r,r));
mchk("total","m0") = sum(r, mchk(r,"m0"));
mchk("total","x0") = sum(r, mchk(r,"x0"));
display mchk;

```

```

*      Impose consistent bilateral trade flows (consumption):
c0(r,rr) = c0(r,rr) + mchk(r,"x0")/mchk("total","x0") * mchk(rr,"m0");

```

```

parameter mktchk;
mktchk(r,"y0") = y0(r);
mktchk(r,"d0") = c0(r,r);
mktchk(r,"x0") = sum(rr,c0(r,rr)) - c0(r,r);
mktchk(r,"y0-d0-x0") = y0(r) - sum(rr, c0(r,rr)) + eps;
display mktchk;

```

```

*      Emissions have a 1:1 relationship with energy use. Initially there is no
emission constraint:
elim(r) = 0;

```

```

*-----
*      Algebraic model formulation in mixed complementarity format (based on
*      calibrated share form)

*      Value shares for calibrated share form:
parameter      theta_e_y(r)      Benchmark cost share of energy in macro production,
                theta_k_kl(r)     Benchmark cost share of capital in value-added,
                theta_r_e(r)      Benchmark cost share of specific resource in energy
                                production,
                theta_l_w(r)      Benchmark cost share of leisure in welfare
                                composite

```

theta_y_a(rr,r) Benchmark cost share of output from region rr in
consumption composite of region r;

theta_e_y(r) = ed0(r)/(ed0(r)+k0(r)+l0(r));
theta_k_kl(r) = k0(r)/(k0(r)+l0(r));
theta_r_e(r) = r0(r)/(f0(r)+r0(r));
theta_l_w(r) = ls0(r)/(ls0(r) + sum(rr,c0(rr,r)));
theta_y_a(rr,r) = c0(rr,r)/sum(rr.local, c0(rr,r));

positive variables

* Activity levels:
Y(r) Macro output,
A(r) Armington production,
E(r) Energy supply,
ED(r) Energy demand,
W(r) Welfare,

* Prices:
P(r) Macro output price,
PA(r) Armington price index,
PW(r) Welfare price index,
PE International energy supply price,
PED(r) Energy demand price,
PL(r) Wage rate,
RK(r) Return to capital,
PR(r) Resource price,
PQ Emission quota price,

* Income level:
RA(r) Representative agent,

* Additional variables:
EMIT(r) Emissions target,
MU(r) CDM incentive subsidy,
TAU(r) CDM emission tax;

equations

* Zero-profit conditions:
ZPRF_Y(r) Zero profit for macro output,
ZPRF_A(r) Zero profit for Armington composite,
ZPRF_E(r) Zero profit for energy supply,
ZPRF_ED(r) Zero profit for energy demand,
ZPRF_W(r) Zero profit for welfare,

* Market-clearance conditions:
MKT_P(r) Supply-demand balance for macro output,
MKT_PA(r) Supply-demand balance for Armington composite,
MKT_PE Supply-demand balance for energy,
MKT_PED(r) Supply-demand balance for energy demand,
MKT_PL(r) Supply-demand balance for labor,
MKT_RK(r) Supply-demand balance for capital,
MKT_PR(r) Supply-demand balance for resources,
MKT_PQ Supply-demand balance for emissions quotas,
MKT_PW(r) Supply-demand balance for welfare composite,

* Income constraint:
I_RA(r) Income balance,

EQ_EMIT(r) Emissions balance,
EQ_MU(r) Constraint for endogenous CDM output subsidy,
EQ_TAU(r) Constraint for endogenous CDM energy tax;

* Zero-profit conditions: $c(x) \geq p(x)$ are complementary with activity
* levels $_{|_} x$

```

ZPRF_Y(r)..      (theta_e_y(r)*(PED(r)*(1+TAU(r)))**(1-sigma) + (1-
                  theta_e_y(r))*(RK(r)**theta_k_kl(r)*PL(r)**(1-
                  theta_k_kl(r)))**(1-sigma))**(1/(1-sigma))
                  =e= P(r)*(1+MU(r));

ZPRF_E(r)..      (theta_r_e(r)*RK(r)**(1-eta) + (1-theta_r_e(r))*PR(r)**(1-
                  eta))**(1/(1-eta)) =e= PE;

ZPRF_ED(r)..     PE + PQ$elim(r) =e= PED(r);

ZPRF_A(r)..      sum(rr, theta_y_a(rr,r)*P(rr)**(1-gamma))**(1/(1-gamma)) =e= PA(r);

ZPRF_W(r)..      PL(r)**theta_l_w(r)*PA(r)**(1-theta_l_w(r)) =e= PW(r);

*               Market-clearance conditions s(p) >= d(p) are complementary with
*               prices _l_ p

MKT_P(r)..       y0(r)*Y(r) =e= sum(rr, (c0(r,rr) * A(rr)) * (PA(rr)/P(r))**gamma);

MKT_PE..         sum(r, es0(r) * E(r)) =e= sum(r, ed0(r) * ED(r));

MKT_PED(r)..     ed0(r)*ED(r) =e= ed0(r) * Y(r) * (
                  (P(r)*(1+MU(r)))/((1+TAU(r))*PED(r)) )**sigma ;

MKT_PL(r)..      le0(r) =e= ls0(r) * W(r) * PW(r)/PL(r)
                  + l0(r) * Y(r)*((P(r)*(1+MU(R)))/(RK(r)**theta_k_kl(r)*PL(r)**(1-
                  theta_k_kl(r))))**sigma)*(RK(r)**theta_k_kl(r)*PL(r)**(1-
                  theta_k_kl(r)))/PL(r);

MKT_RK(r)..      ke0(r) =e= f0(r) * E(r) * (PE/RK(r))**eta
                  + k0(r) * Y(r)*((P(r)*(1+MU(R)))/(RK(r)**theta_k_kl(r)*PL(r)**(1-
                  theta_k_kl(r))))**sigma)*(RK(r)**theta_k_kl(r)*PL(r)**(1-
                  theta_k_kl(r)))/RK(r);

MKT_PR(r)..      r0(r) =e= r0(r) * E(r) * (PE/PR(r))**eta;

MKT_PA(r)..      sum(rr,c0(rr,r))*A(r) =e= (sum(rr,c0(rr,r)))*W(r)*PW(r)/PA(r);

MKT_PW(r)..      W(r)*(sum(rr,c0(rr,r)) + ls0(r)) =E= RA(r)/PW(r);

MKT_PQ$card(elim)..      target =e= sum(rr, ED(rr)*ed0(rr));

*               Income-balance equation:

I_RA(r)..        RA(r) =e=      r0(r)*PR(r) + ke0(r)*RK(r) + le0(r)*PL(r)
                  + PQ*elim(r)*EMIT(r)
                  + PL(r)*(sum(rr,cdmv(rr,r)))
                  - sum(rr, PL(rr)*cdmv(r,rr))
                  + TAU(r) * ed0(r) * ED(r) * PED(r)
                  - MU(r) * y0(r) * Y(r) * P(r);

*               Constraints:

EQ_EMIT(r)$EMIT.UP(r)..      elim(r)*EMIT(r) =G= ed0(r)$elim(r) * ED(r);

EQ_MU(r)..        (evs(r)*PE**(1-sigma) + (1-evs(r))*(RK(r)**kvs(r)*PL(r)**(1-
                  kvs(r)))**(1-sigma))**(1/(1-sigma)) =e=
                  (evs(r)*(PED(r)*(1+TAU(r)))**(1-sigma) + (1-
                  evs(r))*(RK(r)**kvs(r)*PL(r)**(1-kvs(r)))**(1-sigma))**(1/(1-
                  sigma)) / (1+MU(r));

EQ_TAU(r)..       MU(r)*y0(r)*P(r)*Y(r) - TAU(r)*ed0(r)*ED(r)*PE =e=
                  PL(r)*sum(rr,cdmv(rr,r));

*               MCP model definition (complementarity between equilibrium conditions and
*               decision variables):

```



```

model cdm_mcp / ZPRF_Y.Y, ZPRF_E.E, ZPRF_ED.ED, ZPRF_W.W, ZPRF_A.A,
               MKT_P.P, MKT_PE.PE, MKT_PED.PED, MKT_PL.PL, MKT_RK.RK, MKT_PR.PR,
               MKT_PQ.PQ, MKT_PW.PW, MKT_PA.PA,
               I_RA.RA,
               EQ_EMIT.EMIT, EQ_MU.MU, EQ_TAU.TAU /;

*       Benchmark replication with MCP version:

*       Assign initial level values:
Y.l(r) = 1; A.l(r) = 1; E.l(r) = 1; ED.l(r) = 1; W.l(r) = 1;
P.l(r) = 1; PA.l(r) = 1; PW.l(r) = 1; PE.l = 1; PED.l(r) = 1;
PL.l(r) = 1; RK.l(r) = 1; PR.l(r) = 1;

*       No active climate policy in the benchmark equilibrium:
TAU.FX(r) = 0;
MU.FX(r) = 0;
EMIT.FX(r) = 0;
PQ.l = 0;

*       Initial income level:
RA.l(r) = r0(r)*PR.l(r) + ke0(r)*RK.l(r) + le0(r)*PL.l(r) + PQ.l*elim(r)*EMIT.l(r)
          + PL.l(r)*(sum(rr,cdmv(rr,r)) - sum(rr, PL.l(rr)*cdmv(r,rr))
          + TAU.l(r) * ed0(r) * ED.l(r) * PED.l(r)
          - MU.l(r) * y0(r) * Y.l(r) * P.l(r);

cdm_mcp.iterlim = 0;
solve cdm_mcp using mcp;

*       Relax MCP iteration limit for subsequent policy counterfactuals:
cdm_mcp.iterlim = 10000;

*       Fix a numeraire for easing the MCP numerical solution:
pw.fx("OECD") = 1;

*       Illustrative unilateral climate policy constraint: We impose a 20% emission
reduction from BMK for OECD.
target = sum(r,ed0(r)) - 0.2*ed0("oecd");
EMIT.UP("oecd") = +inf;
elim("oecd") = 0.8*ed0("oecd");

solve cdm_mcp using mcp;

*       Now contemplate cooperation through CDM flexibility:
set      cdmlvl Alternative levels of monetary CDM transfers /0*40/;

parameter      welfare      Welfare Impact
               taxrate      Implicit tax rate;

welfare("0",r) = 100 * (W.L(r)-1);

TAU.UP("china") = +inf;
MU.UP("china") = +inf;
MU.LO("china") = -inf;

taxrate("0","oecd") = PQ.L/PE.L * 100;
loop(cdmlvl$cdmlvl.val,

*       Compute CDM transfers from OECD to China as a fraction of BMK labor income
in China
cdmv("oecd","china") = 0.01*(cdmlvl.val/10)*ls0("china");

*       MCP model solution
solve cdm_mcp using mcp;
abort$round(cdm_mcp.objval,5) "CDM model does not solve.";

```

```

welfare(cdmlvl,r)          = 100 * (W.L(r)-1);
taxrate(cdmlvl,"oecd")     = PQ.L/PE.L * 100;
taxrate(cdmlvl,r)$TAU.UP(r) = TAU.L(r) * 100;

);

display welfare, taxrate;

*      Plot results using public domain gnuplot package (which must be downloaded
*      and installed before)
*      See: www.mpsge.org

set      labels(cdmlvl) /0 0, 10 1, 20 2, 30 3, 40 4 /;

$setglobal gp_opt0 "set xlabel 'CDM transfer level -- % CDM host labor earnings'"
$setglobal gp_opt1 "set ylabel 'Welfare Cost -- % EV'"
$setglobal domain cdmlvl
$setglobal labels labels
$libinclude plot welfare

$setglobal gp_opt0 "set xlabel 'CDM transfer level -- % CDM host labor earnings'"
$setglobal gp_opt1 "set ylabel 'Implicit emission tax rate -- %'"
$libinclude plot taxrate

```

Appendix C. Elasticities of substitution

Table C1. Elasticities of substitution adopted in the model application.

Sector	<i>esub-KLE-M</i>	<i>esub-KL-E</i>	<i>esub-K-L</i>	<i>esub-E</i>	<i>esub-M</i>	<i>esubd</i>	<i>esubm</i>
oil	0.50	0.50	1.26	0.50	0.30	2.10	4.20
gas	0.50	0.50	0.65	0.50	0.30	5.00	10.00
ele	0.50	0.50	1.26	0.50	0.30	2.80	5.60
C	0.30	0.50	0.50	0.00	0.50	0.00	0.00
COL	0.50	0.50	0.20	0.50	0.30	3.05	6.10
CRU	0.50	0.50	0.20	0.50	0.30	5.00	10.00
EIT	0.50	0.50	1.26	0.50	0.30	3.28	6.69
TRN	0.50	0.50	1.68	0.50	0.30	1.90	3.80
AOG	0.50	0.50	1.27	0.50	0.30	2.54	6.54
<i>esub-KLE-M:</i>	Elasticity of substitution between KLE and M						
<i>esub-KL-E:</i>	Elasticity of substitution between KL and E						
<i>esub-K-L:</i>	Elasticity of substitution between K and L						
<i>esub-E:</i>	Elasticity of substitution within energy composite						
<i>esub-M:</i>	Elasticity of substitution within material composite						
<i>esubd:</i>	Elasticity of substitution between imports and products						
<i>esubm:</i>	Elasticity of substitution between imports						

Sources: Böhringer et al. (2011), Narayanan and Walmsley (2008).

Appendix D. Regional CDM impacts

So far, most CDM projects have been concentrated in a small number of countries. In 2012, almost 80% of all projects in the CDM pipeline are hosted by China and India, 14% by countries in Latin America, in particular by Brazil and Mexico, and 4% by countries in Africa.¹⁴ In this section, we apply the incentive-compatible CDM framework to analyze the efficiency implications of concentrating CDM investments on those regions.

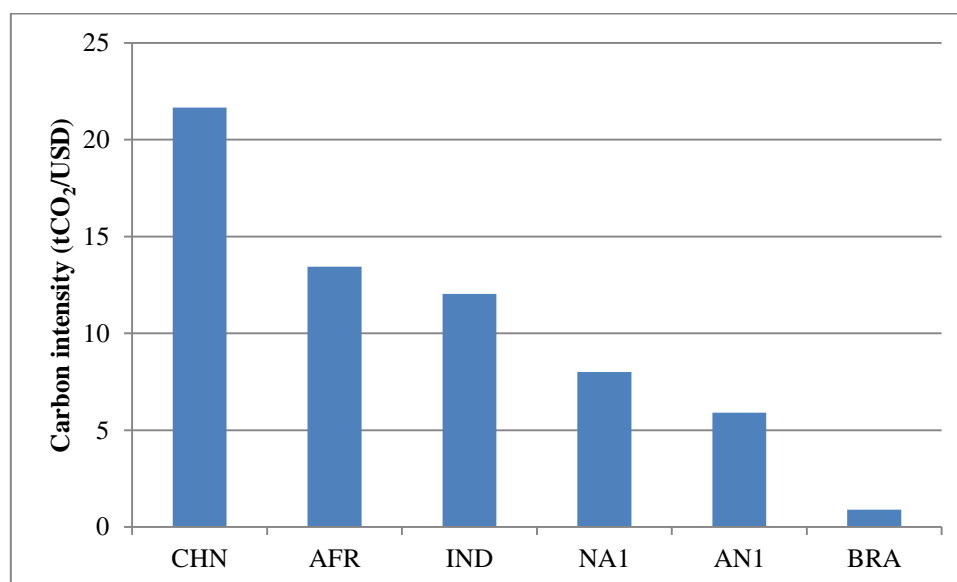


Figure D.1. Carbon intensity of the electricity sector in 2004 in China (CHN), Africa (AFR), India (IND), Brazil (BRA), other non-Annex I countries (NA1), and Annex I countries (AN1).

Figure D.1 shows the carbon intensity of the electricity sectors for a selection of countries which are active in the CDM.¹⁵ In most of those countries, the electricity sector has the greatest carbon intensity (an exception is Brazil whose transport sector is more carbon intensive). China's electricity sector has by far the greatest carbon intensity. Africa's carbon intensity is 38% lower and India's 44% lower, but they are still 68% and 50% higher, respectively, than the average carbon intensity in non-Annex I countries. Brazil's carbon intensity is 96% lower than that of China and 89% lower than the average carbon intensity in non-Annex I countries. The distribution of carbon intensities suggests that there exists a great potential for reducing emissions by implementing efficiency-improving CDM projects in China, Africa, and India, but little potential in Brazil.

In the following, we use our CGE model and the incentive-compatible CDM modeling framework to determine the economically efficient volume of CDM investment (from the standpoint of Annex I countries) if those countries are chosen as CDM hosts. Table D.1 provides an overview of the CDM-specific results obtained. China attracts a volume of USD 8.65 billion in CDM investments when it is chosen as host country. For this amount, Annex I

¹⁴ http://www.cdmpipeline.org/regions_7.htm [accessed 13 February 2013].

¹⁵ The data is obtained from the same database which is used to calibrate the CGE model employed in this study (GTAP 7.1 with reference year 2004).

countries receive about 688 MtCO₂ in CDM offsets, which reduces their domestic carbon price by 30%, from 34 USD/tCO₂ to 24 USD/tCO₂. In comparison, Africa and India attract 79% and 55% less CDM investments which yield 84% and 62% less CDM offsets, respectively, when they are chosen as host countries. The (implicit) price for CDM offsets is about half of the domestic carbon price in Annex I countries for all three host countries. In contrast, the economically efficient volume of CDM investment is marginal when Brazil is chosen as a host country.

Table D.1. Overview of CDM-specific results

Parameter	Unit	AFR	BRA	CHN	IND
CDM transfer	(billion USD)	1,85	0,21	8,65	3,91
CDM offsets	(MtCO ₂)	107,00	7,00	688,19	259,49
CDM price	(USD/tCO ₂)	17,32	29,42	12,56	15,07
PCO ₂ in AN1	(USD/tCO ₂)	33,66	36,30	23,63	31,01

Figure D.2 displays the welfare effects for the case that Annex I countries undertake CDM investments in the host countries considered. Welfare improvements for Annex I countries relative to the reference cap-and-trade scenario range from 33% when China is chosen as a host country, over 14% and 8% when India and Africa are chosen, to almost no effect when Brazil is chosen. The welfare improvements in the host countries are 164% in China, and 36% and 9% in India and Africa, respectively. Brazil's welfare improves by 45% when chosen as host country, despite the low level of efficient CDM investments in Brazil.

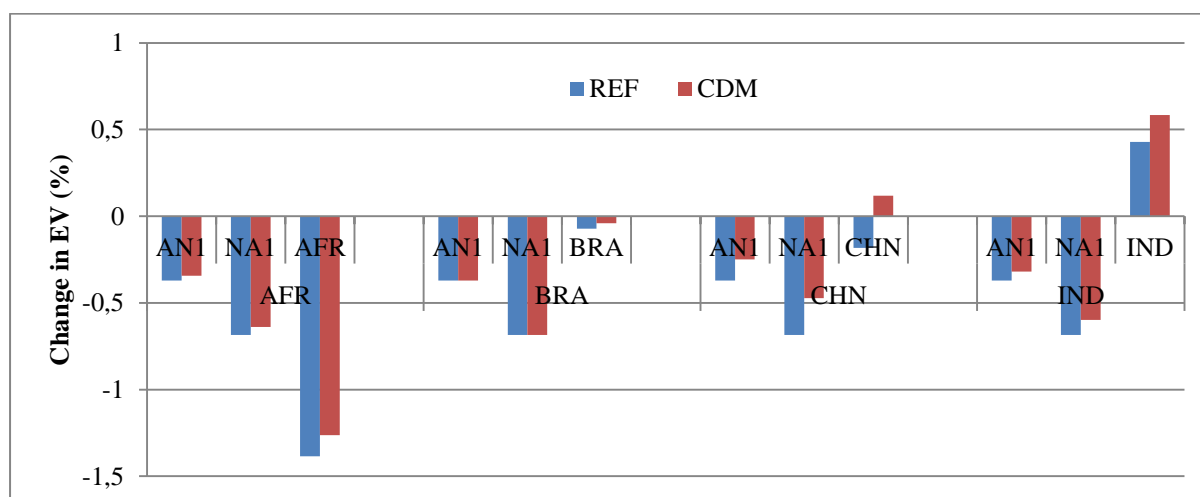


Figure D.2. Welfare impacts in the reference cap-and-trade scenario (REF) and in the incentive-compatible CDM scenario (CDM) when Africa, Brazil, China, and India are chosen as host countries.

Beyond the investment's effects on the donor and host countries, there are general-equilibrium feedbacks on other non-Annex I countries. Those occur primarily because Annex I countries do not decrease their demand for imports from non-Annex I countries as much

when having access to CDM credits as when faced with meeting emissions targets solely through domestic reductions. Figure D.2 indicates that such positive feedbacks can improve non-Annex I countries' relative welfare by 31% when China is chosen as host country, and by 13% and 7%, respectively, when India and Africa are chosen as host countries; there is no significant feedback effect when Brazil is selected.

The regional results obtained by representing the CDM in the incentive-compatible CGE framework presented in this study broadly agree with the current regional distribution of CDM projects. It is economically most efficient to invest in China and India which are the countries currently hosting the most projects. However, the CGE analysis also shows that from a macroeconomic efficiency standpoint, it may be beneficial to increase CDM investments in Africa, and to undertake comprehensive cost-benefit analyses on the project level when investing in Brazil to assess the potential effectiveness of such investment.¹⁶

¹⁶ Note that this analysis does not take into account transaction costs, investment climates, and CDM sectors other than electricity, all of which could alter the economically efficient distribution of CDM investments. With regards to the former, an analysis for the German Ministry for the Environment (<http://www.jiko-bmu.de/files/english/application/pdf/cdm-markt-brasilien-english.pdf>, accessed 13 February 2013) has underlined the good investment climate and market access in Brazil, which may contribute to the current attractiveness of Brazil for CDM investments.